Levitation of a Small Carbon Sail by Visible Radiation in Rarified Atmosphere

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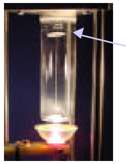
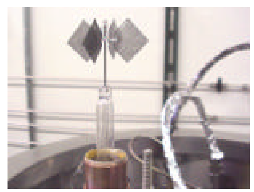
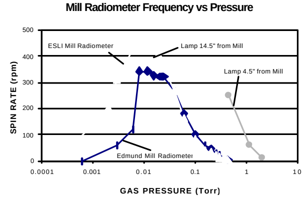


Crookes Mill 'Radiometer'

- Thermally driven
  - Cold gas molecules exchange heat and momentum with radiantly heated vane
  - Continuous thrust requires mfp ~ or > vane size
- Rotation rate is maximal for P~1 Pa
  - Decreases at higher pressure because boundary layer forms halting momentum exchange
  - Decreases at lower pressure because fewer molecules act





'Radiometer' Gas-Kinetic Pressure

- Consider 85-km altitude
  - Mfp ~ 1 cm
  - P ~ 1 Pa
  - T ~ 200 K
- Use radiation sufficient to maintain ΔT~100 K
  - Roughly 10 kW/m2
- Supports a 12-g/m^2 sail against gravity

$$\Delta P_{gas-kinetic} = P_0(\phi_1 - \phi_2) = P_{atm}\frac{\rho}{\rho_{atm}}(\phi_1 - \phi_2)$$

$$\phi_i = \frac{\alpha_{p,i}}{2}\left[\left(\frac{T_i}{T_0}\right)^{1/2} - 1\right]$$

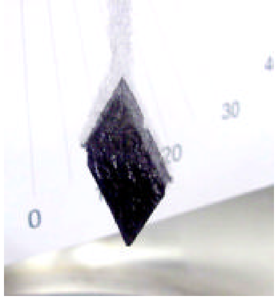
atmospheric pressure P_{atm}	Pa	1.01E+05
density ratio	-	1.00E-05
ambient temperature	K	200
pressure accommodation coef, α_1	-	0.8
pressure accommodation coef, α_2	-	0.2
temperature of surface 1	K	350
temperature of surface 2	K	250
ϕ_1	-	0.129
ϕ_2	-	0.012
thermal-molecular thrust	Pa	0.12
areal mass supported, σ	g/m^2	12.1

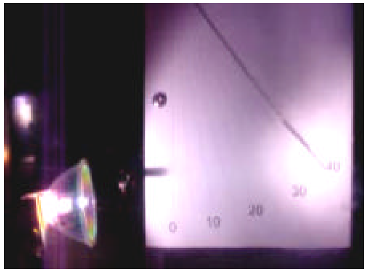
ESLI Vane Materials

- Thin carbon membrane with textured surfaces (~5 g/m^2)
- Supportable with 3D carbon fiber microtruss (10 g/m^2)
- Levitation of 5 g/m^2 requires 0.05 Pa

Pendulum Testing

Pendulum testing normalizes thrust to 1 G





Levitation Demonstration

Have observed levitation of 5-g/m^2 carbon sail with incandescent lamp up to 300 W with pressure throughout 0.2 - 20 Pa

Desired Improvements

- Develop higher performance materials and power conditioning
- High coupling coefficient ~ N/kW
- More thrust at higher pressure
  - Net lift at lower altitude in Earth atmosphere
  - Net lift at the surface of Mars (~500 Pa CO_2)
- Reverse thrust, pulling toward the source

Applications

- ‘Hovering Earth Platform’ @ ~60-100 km
  - Communications; Reconnaissance
  - $5 g/m^2 = 5{,}000 kg/km^2$; Solar thermal = 1 GW
- Low-cost environment for Gossamer test
  - Flight dynamics and control
  - Field gossamer instrumentation and communications
- Launching Gossamer Spacecraft from Earth
- Planetary exploration (winds? dust devils?)

Carbon Sails

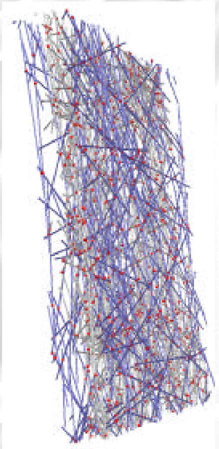
Microwave – Laser – Solar

Developments 2000

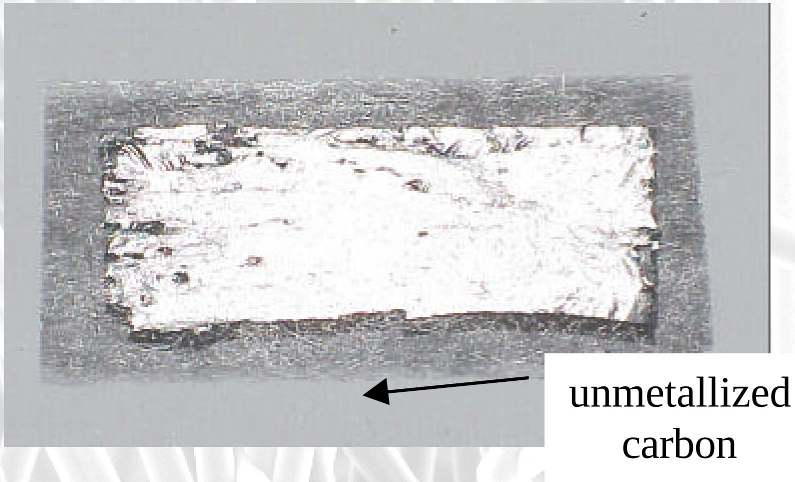
Energy Science Laboratories Inc.

Timothy R. Knowles

Carbon-Carbon Sails



- 3D carbon fiber microtruss structure
  - Lightweight, stiff, bendable
  - High temperature (2500 K)
  - Elastic self-deployment
- Carbon films integrated
  - Thin, flexible, smooth
  - Metallize with Ag, Mo
    - High reflectivity (front)
    - High emissivity (back)

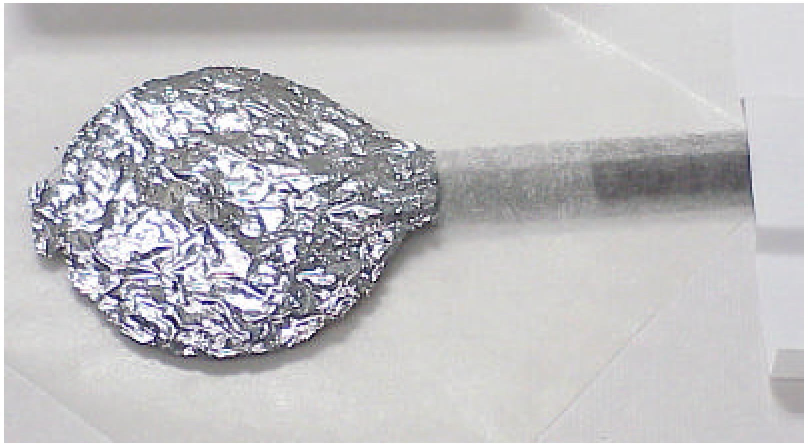


Carbon-Carbon Sail (4-g/m^2 film on 7-g/m^2 microtruss)

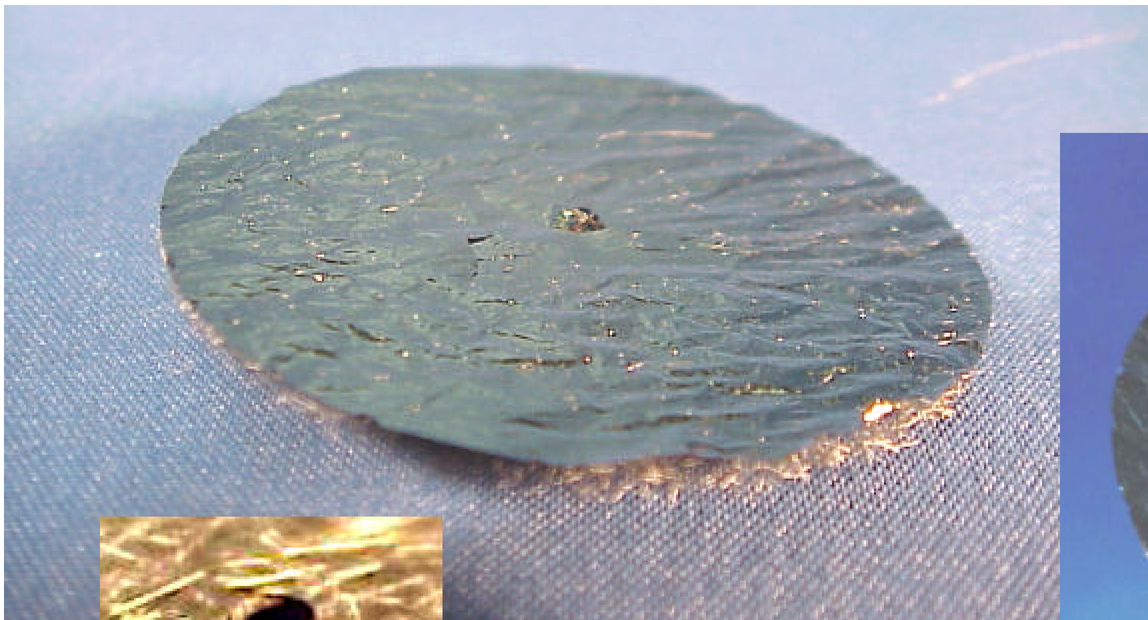
ESLI

Reflective Laser Sails

- Carbon membrane
  - Areal mass 3 g/m^2
  - Th. expansion 3 e-6/K
- Carbon bonding to microtruss at high-T
- Molybdenum sputter coating ~50 nm

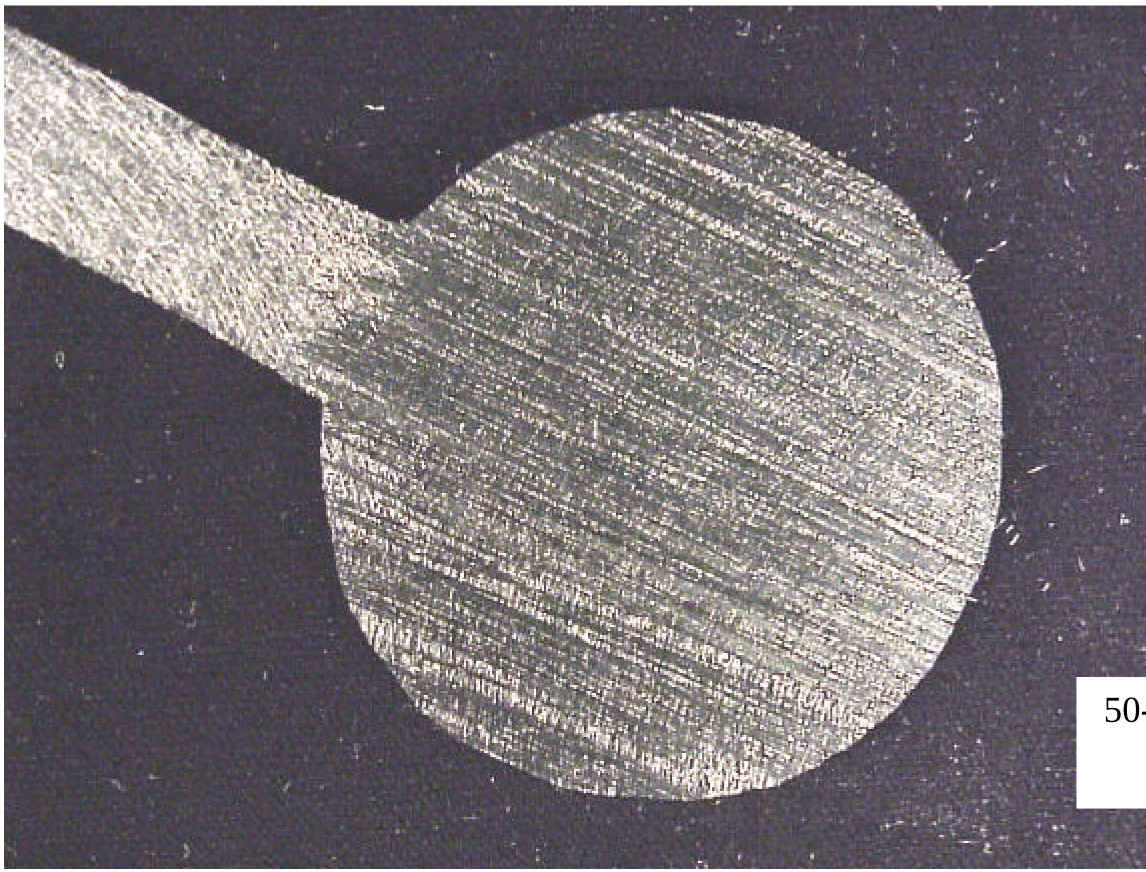


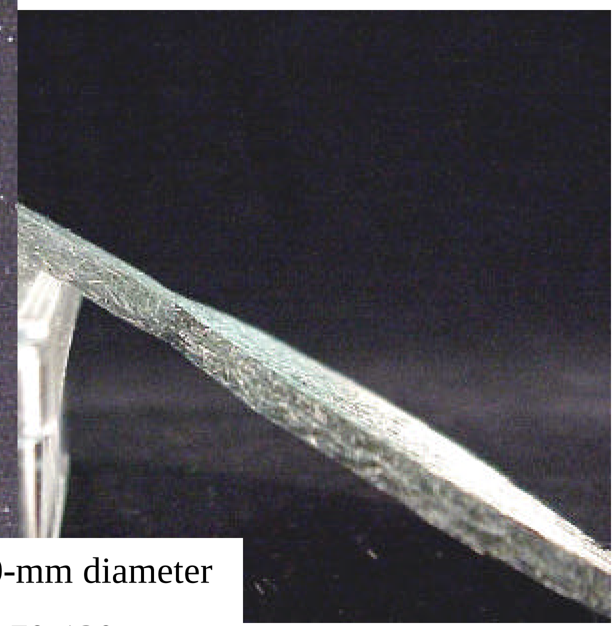
Metallized Laser Flight Sails



moly sputter coat

Reinforced Carbon Microtruss





50-mm diameter

70-130 mg